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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

**METHOD OF USING CASCADED SWEEPS FOR SOURCE CODING AND
HARMONIC CANCELLATION**

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CROSS REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority from United States Provisional Patent Application No. 60/241,211 filed on October 17, 2000.

FIELD OF THE INVENTION

[0002] This invention relates to the field of geophysical prospecting and, more particularly, to acquiring seismic vibrator data.

BACKGROUND OF THE INVENTION

[0003] The seismic exploration industry uses acoustic impulses to impart sonic vibrations into the earth to delineate subsurface structure for mineral exploration and development. These acoustic impulses may be from an explosive, implosive, swept-frequency (chirp) or random source. A recording of the acoustic reflection and refraction wavefronts that travel from the source to a receiver is used to produce a seismic field record. Variations in the travel times of reflection and refraction events in these field records indicate the position of reflection surfaces within the earth. The analysis and correlation of events in one or more field records in seismic data processing produces an acoustic image that demonstrates subsurface structure. The acoustic images are used to find valuable mineral deposits.

[0004] The swept-frequency or chirp type seismic source may utilize a relatively long pilot signal such as 2 to 15 seconds to assure sufficient energy is imparted to the earth. The swept-frequency or chirp type source method relies on signal compression to compress the

signal and ensure sufficient vertical resolution to resolve the position of subsurface reflectors. Signal compression generally is called deconvolution, with many techniques well known in the art of seismic data processing. Deconvolution of sweep or chirp signals compresses the source signal into a much shorter signal representative of a subsurface reflective boundary. The accuracy and effectiveness of any deconvolution technique is directly related to how well the source signal is known or understood. Most deconvolution operators are derived from statistical estimates of the actual source waveform.

[0005] With a swept frequency type source the energy is emitted in the form of a sweep of regularly increasing (upsweep) or decreasing (downsweep) frequency in the seismic frequency range. The vibrations are controlled by a control signal, which can control the frequency and phase of the seismic signals.

[0006] When only one seismic source is used, the seismic surveys can be very time-consuming. With modern signal processing methods this period could be shortened if more than one seismic source could be used simultaneously. Multiple sources can be used if some means for distinguishing between signals emanating from the different sources can be provided. Further, the vibrational source generates harmonics which, in certain circumstances, can have an energy approaching or even exceeding the fundamental, and which can crossfeed with signals from other sources, giving misleading results when the signals are processed to separate the signals from each source. In addition, the harmonics are a source of noise and can mask weak reflection signals from deeper layers.

[0007] U.S. Pat. No. 3,885,225 to Anstey et al proposes a method to distinguish between multiple sources. Anstey et al is directed to a method and apparatus for broad-line seismic profiling, using several vibrators simultaneously emitting signals. The normal emission frequency bandwidth is divided into several parts that are allocated to individual vibrators in a sequence of separate emissions, in such a way that the several vibrators radiate mutually exclusive frequencies at any one time. The detected signals are separated on the basis of frequency to represent the individual signals from each vibrator. The frequency limitation on each individual vibrator reduces the sensitivity of the survey. Harmonic distortion in the vibrators or their coupling with the ground can inhibit signal separation from different generators, this '225 patent makes no attempt to remove or reduce this distortion.

[0008] Another method of signal separation from multiple vibratory sources using phase shifting of the signals on different sweeps is disclosed in U.S. Pat. No. 4,715,020 to Landrum. However, the problem of nonlinear distortion and crossfeed is not addressed in this patent.

[0009] A method for attenuating harmonic correlation noise caused by harmonic energy output from seismic vibrators was developed by Reitsch as disclosed in U.S. Patent 4,042,910. The method includes the step of generating a plurality of sweep signals in series and with the phase of each succeeding sweep signal being shifted relative to the previous one by a predetermined phase angle that is a fraction of 2π . The generated signals are separately recorded and transformed by inverse phase shifting before being added or stacked in a conventional manner. Using this method, a series of N sweep segments are output by the

vibrators (one for each record) that differ only in phase. Correlation noise up the Nth harmonic is attenuated. This method provides a method of suppressing harmonics using phase shifting, but only for a single vibratory source, and crossfeed is not addressed.

5 [0010] U.S. Pat. No. 4,823,326 to Ward, claims a method for separating seismic records derived from multiple, concurrently operated vibrational seismic sources, with reduced harmonic distortion.

10 [0011] U.S. Pat. No. 4,982,374 to Edington and Khan is a method for reducing the distortion and crossfeed from any selected order harmonic for any number of vibratory seismic sources operated concurrently, at the same time providing for separation of the signals from the different sources and for improving the signal-to-noise ratio. After determining the highest order harmonic likely to cause distortion, a number of sweeps of each source in each position is selected. This number depends upon the number of sources and the highest order
15 harmonic to be suppressed. Initial phase angles for each sweep of each source are then selected to permit signal separation while suppressing harmonics up to and including that highest order harmonic.

20 [0012] U.S. Patent 5,410,517 to Andersen discloses a method of cascading sweep segments to suppress unwanted harmonic energy. The method uses sweep segments having varying phase angles such that harmonic energy in the correlated wavelets is attenuated. According to the method, a first cascaded sweep sequence is generated containing N sweep segments linked end-to-end. The N sweep segments are substantially identical, except that the initial

phase angle of each sweep segment within the sweep sequence is progressively rotated by a constant phase increment of about $360/N$ degrees. A second cascaded sweep sequence is generated consisting of: (i) N consecutive sweep segments linked end-to-end which correspond to said first cascaded sweep sequence, and (ii) an additional sweep segment
5 linked to the N consecutive sweep segments which is positioned and phased so as to substantially suppress harmonic ghosts during correlation. One of these cascaded sweep sequences is used for the vibrator sweep sequence and the other is used for the correlation reference sequence.

10 SUMMARY OF THE INVENTION

[0013] A method of seismic surveying using vibrational seismic energy sources activated by sweep signals which may be concatenated together. A number of seismic sources are selected, a highest order of harmonic energy able to cause significant distortion is selected,
15 and a number of sweeps, or sweep segments to be combined together, is determined and selected to suppress unwanted harmonics and to separate source signals. The amplitudes of the correlation operators may be adjusted by measured ground force signal energy prior to correlation to balance and attenuate harmonic energy. The correlation operator may be the pilot sweep signal, the ground force signal or derived components of the pilot or ground
20 force.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention and its advantages will be better understood by referring to the

following detailed description and the attached drawings in which:

FIG. 1 illustrates the overall structure of the invention and its objectives.

FIG. 2a illustrates a cascaded sweep with phase rotation.

FIG. 2b illustrates a field record containing harmonic energy.

5 **FIG. 3a** illustrates a cascaded sweep sequence with phase rotation that may be used to suppress up to the fifth harmonic.

FIG. 3b shows is a schematic illustration of one embodiment of the invention in which the correlation signal comprises the sweep signal augmented by a sweep segment.

10 **FIG. 3c** shows is a schematic illustration of one embodiment of the invention in which the correlation signal comprises the unaugmented sweep signal.

FIG. 4 illustrates a field record after application of the present invention.

FIG. 5 illustrates two sweep sequences that may be used for two sources performing concurrent data acquisition.

15 **FIG. 6** illustrates a field record acquired with two sources before application of the present invention.

FIG. 7a illustrates an application of the present invention to separate the signal from one source of the concurrent acquisition demonstrated in FIG 6.

FIG. 7b illustrates an application of the present invention to separate the signal from the second source of the acquisition demonstrated in FIG 6.

20 **FIG. 8** illustrates a correlation of a vibrator signal with the pilot signal.

FIG. 9 illustrates a correlation of a vibrator signal with the ground force signal.

FIG. 10 illustrates a correlation with the ground force signal after sweep phase rotation for harmonic suppression.

FIG. 11 illustrates a correlation with the pilot sweep on phase-rotated sweep segments with noise added.

FIG. 12 illustrates a correlation with the ground force signal on phase-rotated sweep segments with noise added.

5 **FIG. 13** is a schematic illustration of the correlation process when ground force signals are used.

[0015] While the invention will be described in connection with its preferred embodiments, it will be understood that the invention is not limited thereto. On the contrary, it is intended
10 to cover all alternatives, modifications, and equivalents that may be included within the spirit and scope of the invention, as defined by the appended claims.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

15 [0016] The overall structure of the invention is best understood with reference to **Figure 1**. This will aid in understanding the detailed description that follows. The method of the invention 1 as shown in **Figure 1**, uses cascaded sweeps for acquiring seismic data. The purpose of the invention 3 is to be able to separate data from a plurality of sources as well as attenuate harmonics. In one embodiment of the invention, this is achieved by correlating
20 a reflected seismic signal with a theoretical, predetermined signal related to the pilot sweep used to drive the vibrators 5. This may be done for any number of sources and any desired level of harmonic cancellation 9. Broadly speaking, when the correlation signal is related to the pilot sweep, each vibrator is swept with N sweep segments and the correlation signal

comprises $N+1$ segments 13.

[0017] In an alternate embodiment of the invention, ground force signals are measured at the vibrators and the correlation signal is related to the ground force signals 7. As with the first method, any number of sources may be used and any degree of harmonic cancellation is possible 11. As with the first embodiment, vibrators are swept with N sweep segments; however, the correlation signal comprises $N+2$ segments of recorded ground force data. This is explained below.

[0018] The present invention is a seismic data acquisition method of using phase rotated sweeps and cascaded phase rotated sweep segments that may be used for multiple sources operated concurrently. The invention provides for suppression of harmonic ghosts and crossfeed energy while concurrently using multiple sources, leading to reductions in survey acquisition time and improved data quality. To the extent that the following description is specific to a particular embodiment or a particular use of the invention, this is intended to be illustrative and is not to be construed as limiting the scope of the invention.

[0019] Vibrator crews may be more efficient when the field effort involves combining sweeps that would normally be output at a vibrator point (VP) into a cascaded sequence of sweep segments such as shown in Figure 2a. This series of five cascaded sweep segments with the phase sequence 0, 72, 144, 216, and 288 degrees may be used to suppress up to the fifth harmonic (the 2nd, 3rd, 4th and 5th) when one source is used. The field time required to record data for these five sweep segments is much shorter than that required to record them

separately because only a single listen period is required. However, even if we build the cascaded sweep segments using a phase rotation method for canceling harmonics and crosscorrelate using the same cascaded sweep pilot signal, harmonic correlation noise results both before and after each wavelet in the correlated data. Correlation noise caused by cascaded sweep segments is evident in the correlated record of **Figure 2b**.

[0020] In 1994, in U.S. Patent 5,410,517 to Andersen, which patent is fully incorporated herein by reference, disclosed a method for attenuating the harmonic correlation noise caused by cascading the sweep segments of **Figure 2a**. He found that forming a correlation pilot signal by adding another sweep segment to the sequence shown in **Figure 2a**, (i.e. placing a replica of the last sweep segment in front of the first sweep segment of **Figure 2a**), attenuated the harmonics. Andersen's method and claims specify that the phase rotation sequence of the individual sweep segments comprising the cascaded sweep must be progressive $+2\pi/N$ radians, where N is the number of sweep segments.

[0021] The present invention combines a method for source coding and harmonic cancellation when using multiple sources with a technique for cascading phase rotated vibrator sweep segments. In one embodiment of the invention, cascading is similar to U.S. Patent 5,410,517 in that the reference pilot or correlation signal contains N or $N+1$ cascaded sweep segments. However, the method for determining the phase sequencing for the cascaded pilot sweep segments in the '517' patent is rigid in that phase rotations are progressive and determined solely by dividing 2π by the number of sweep segments. Following the scheme taught in the '517 patent does not allow the flexibility necessary to

implement multiple sources operating coincident in time. The '517 patent method actually excludes the possibility of using multiple sources concurrently because the crossfeed harmonic cancellation requirement can not be achieved. Combining a method of cascading phase rotated sweep segments with a technique for source coding resulting in source signal separation allows for using multiple sources concurrently as well as suppression of harmonic ghosts and crossfeed energy.

[0022] In an embodiment of the present invention one or more sets of vibrators generate longer than normal output signals that consist of N cascaded, normal-length sweep segments. If more than one set of vibrators is used, they are located at different VP's. The recording is equal to N times the normal-length sweep time plus a single listen time (correlated record length). The recording time is therefore much shorter than recording a listen time for each of the N sweep segments. Each of the N cascaded sweep segments is phase rotated for source coding and suppression of harmonics. The field effort may be made more efficient with this method, as the total survey time is reduced.

[0023] For example, using one vibrator source group and suppressing up to the 5th harmonic may be accomplished with 5 sweep segments having phase rotations of 0, 144, 288, 72 and 216 degrees as shown in Figure 3a. Suppressing up to the 7th harmonic with 7 sweep segments may be accomplished with phase rotations of 0, 102.86, 205.71, 308.57, 51.43, 154.29 and 257.14 degrees. To suppress up to the 8th harmonic with 8 sweep segments, a sequence of phase rotations for the sweep segments may be 0, 135, 270, 45, 180, 315, 90 and 225. For efficiency in the field effort, the vibrator sweep will contain N segments and the

correlation operator will contain $N+1$ segments.

5 [0024] Figure 3a shows the cascaded sweep sequence for a preferred embodiment of the method of the present invention using one set of vibrators and for canceling harmonics up to the fifth harmonic. The sweep sequence is not progressive. The result of crosscorrelating data with the sweep segments shown in Figure 3a (with an additional sweep appended) is shown in Figure 4 where the harmonics have been eliminated. Comparing this result to the crosscorrelated data of Figure 2b, which did not have the added sweep segment concatenated to the correlation operator, demonstrates harmonics have been eliminated.

10 The method of this embodiment is illustrated in Figure 3b for one vibrator. Data segments A', B', C' and LISTEN correspond to 3 sweep segments and a listen time following the end of the sweep. The correlation signal comprises sweep segments C, A, B, C.

[0025] In another preferred embodiment of the present invention, the data may be acquired using, for example the sweep sequence of Figure 3a. During data processing the portion of the data recorded during the first sweep segment may be combined with the recording period 'listen time,' that is the period after the sweep sequences. Alternatively, this first sweep portion of the data recording may be combined with the 'listen time' portion of the field data recording during acquisition. It is straightforward to apply this to multiple sources operating concurrently. This method is illustrated in Figure 3c where, as in Figure 3b, there are three data segments A', B', C' followed by a listen time LISTEN. In the augmented data set, the data from the period A' is added to the data during the listen time and correlation is performed using the correlation operator A, B, C.

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5 [0026] If multiple vibrator sources are to be used concurrently, there needs to be a way to separate the source signals. Edington and Khan developed a phase rotation scheme disclosed in U.S Patent 4,982,374 that did not envision cascaded sweep segments but provided simultaneous source coding and separation of multiple sources as well as cancellation of crosscorrelation harmonic noise. U.S. Patent 4,982,374 is incorporated herein by reference.

10 [0027] In the present invention, recorded data are crosscorrelated with a cascaded-sweep pilot signal for each set of vibrators. The correlation operator reference signal or the vibrator sweep signal may contain N or N+1 cascaded sweep segments, but the phase sequencing of the sweep segments is chosen so that signals from concurrently operating sources may be separated. Whether the additional sweep segment is placed on the correlation operator or in the vibrator sweep sequence, the first and last sweep segment of the sweep segment series containing the additional segment will have identical initial and final sweep segments. Crosscorrelation then yields the compressed data result from each set of vibrators and so the source signals may be made separate datasets. The correlation noise caused by both the source harmonics and the cascaded sweep segments is greatly attenuated, making the use of cascaded sweep segments acceptable and applicable to concurrent data acquisition by more than one source.

20 [0028] The Edington and Khan patent teaches a method to determine phase rotations for signal separation. Figure 5 illustrates the cascaded sweep sequence for two sets of vibrators allowing for signal separation and for canceling up to the fifth harmonic (i.e., canceling the 2nd, 3rd, 4th and 5th harmonics). For this example, the phase sequence for the first vibrator or

vibrator group, Vib 1, is 0, 102.86, 205.71, 308.57, 51.43, 154.29 and 257.14 degrees. Note, as stated previously in the single vibrator examples, that Vib 1 sequence alone will suppress up to the 7th harmonic. The second concurrently sweeping vibrator or vibrator group, Vib 2, will have a sweep sequence phase rotation of 0, 257.14, 154.29, 51.43, 308.57, 205.71 and 102.86 degrees. Using the Vib 1 and Vib 2 cascaded sweep segments concurrently, only up to the 5th harmonics are suppressed in contrast to the single vibrator example. Figure 6 shows the first portion of an uncorrelated field record acquired with sweep series Vib 1 and Vib 2, indicating that the two sources are at opposite ends of the recording spread. Figures 7a and 7b display the separated record for each of the vibrator sources of Figure 6 with harmonic noise cancelled.

[0029] The sweep segment series have been illustrated as sequentially adjacent, but also the invention may be practiced with the sweep series segments additively overlapped. For example, as one 10-second long sweep segment is within 2 seconds of finishing the next sweep segment may begin. For a sweep series containing 7 10-second sweeps, this would represent a significant time saving for the acquisition effort.

[0030] Each sweep segment comprising the cascaded sweep segment series is identical except for their respective phase rotations. However, they can be of any type, including linear or nonlinear up sweeps, down sweeps or even pseudo-random sweeps. Examples of pseudo-random sweeps are described in Goder, A., 1994, Minimum phase correlation of pseudo-random vibrator signals, 64th Ann. Internat. Mtg. Soc. of Expl. Geophys., 884-885 and Cunningham, A. B., 1979, Some alternate vibrator signals, *Geophysics*, v. 44, pp 1901-

1921)

5 [0031] The phase rotation sequence allowing signal separation is equivalent to the phase rotation sequence with a constant added. In other words, the phase rotation sequence may be made more general by simply adding a constant to each phase term of the series. For example, if $S1 = 0, 144, 288, 72$ and 216 , and $S2 = 0, 216, 72, 288$, and 144 , then equivalent series having the same harmonic cancellation and signal separation are $S3 = 10, 154, 298, 82$ and 226 , with $S4 = 10, 226, 82, 298$ and 154 . It should be noted that when a single vibratory source is used, the first and last columns of the table defined in Edington should
10 not be used.

[0032] The discussion above was related to embodiments of the invention wherein the correlation signal is related to the pilot sweep signal used for driving the vibrators. In another embodiment of the present invention the phase rotated sweep segment series is
15 cross-correlated with the ground force (GF) signal rather than the pilot or the pilot with a repeated segment. The GF signal is a representation of the energy actually transmitted by the vibrator into the earth, and may be different than the pilot reference sweep. In general, the GF signal contains harmonics and subharmonics due to nonlinear coupling with the ground surface. Ground force signal may be measured by the method as disclosed in U.S.
20 Patent Number 6,161,076 to Barr et al., incorporated herein by reference, or any other method. GF signal measurement is a common practice, and there are several ways known in the art to acquire these measurements.

[0033] For example, the GF signals may be measured by one or more methods from different locations on and near the vibrator. The various measurements may be placed on auxiliary channels during acquisition of survey data. Saving the GF measurements to tape or memory allows for further processing, for instance, in the processing center. The GF signals may be conditioned by various methods known in the art, for example by substantially equalizing the measurements among vibrators or vibrator groups, or combining signals to create weighted sum representations of ground force. These GF signals or their further processed forms may then be used for correlation with the field records or to create other filters.

[0034] It has long been known that correlating a seismic record with the measured ground force signal produces undesirable cross-correlation terms between the fundamental and higher order harmonics. This effect may be seen in Figure 8 where a pilot was used as the correlation operator, and in Figure 9 where the correlation was performed with the GF signal. The harmonic energy from the harmonics' crosscorrelation terms spreads out away from the center of each wavelet and may mask weaker reflections.

[0035] The major problem with correlating with the pilot signal is that much of the energy output by the vibrator is not present in the resulting records. In other words, the harmonic energy output from the vibrator is not constructively utilized. This invention utilizes harmonic energy output from the vibrator.

[0036] Figure 10 represents the result of using a GF signal, which contains higher order harmonic energy, as the correlation operator applied to a noise free model where the sweeps

have been rotated to suppress unwanted harmonic energy. If the amplitudes of the harmonic energy are constant between individual sweeps, the harmonic energy will be eliminated; if the amplitudes are different, the harmonic energy will be attenuated.

5 [0037] Amplitude scaling of the correlation operator (whether the operator is a vibrator sweep pilot or a measured GF) may be used to compensate for differing, time-variant vibrator outputs during different sweeps. The vibrator output is measured using the ground force signal so that a scaling operator may be created. For example, a scaling operator may be created that balances amplitude variations occurring between the different sweeps for a
10 vibrator source. Balancing or equalizing the amplitudes of the output sweeps will tend to equalize the harmonic energy; equalization of harmonic energy among differing sweeps enhances attenuation of unwanted harmonic energy.

15 [0038] Another amplitude scaling operator may be formed to enhance signal separation between sources rather than just source harmonic cancellation for a particular source sweep series. Effective and useful source signal separation is at least partly dependent on amplitude relationships of energy emanating from concurrently operating sources as well as their phases. A similar amplitude compensation operator to those for amplitude compensation between and among sweeps at a particular source may be formed that will
20 ensure that desired cancellation (and hence signal separation) properly occurs between concurrently operating sources.

[0039] Using the GF signal with properly rotated sweeps produces results superior to using

the pilot sweep correlation operator. The signal to noise ratio is lower when the pilot is used as can be seen in **Figure 11** when compared to **Figure 12**, the result of phase rotated sweeps correlated with the GF signal.

5 **[0040]** Using the GF signal as the correlation operator can also be applied to the method of phase rotating cascaded sweep segments similar to the technique outlined above. The usual case, however, will call for appending two sweep segments on to the correlation operator, one on the beginning of the operator, the other on the opposite end. A cascaded sweep made up of N segments would become a cascaded GF correlation operator with N+2 segments.

10 For example, for the vibrator sweep segment series containing phases 0, 144, 288, 72 and 216, the correlation operator would be formed from the measured GF signal. The initial and final segments of the vibrator sweep GF signal would be copied and appended to opposite ends. This measured GF signal recorded from the output of the example five segment vibrator sweep would become the basis for a seven sweep segment GF correlation operator

15 consisting of the following phase series: 216, 0, 144, 288, 72, 216 and 0. The correlation process is illustrated in **Figure 13** for three data segments A', B', C', (LISTEN) wherein the correlation signal comprises C, A, B, C, A.

20 **[0041]** It should be understood that the invention is not to be unduly limited to the foregoing which has been set forth for illustrative purposes. Various modifications and alternatives will be apparent to those skilled in the art without departing from the true scope of the invention, as defined in the following claims